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by Yu. A. Sklyarov

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CALCULATION OF CERTAIN ERRORS OF BOLOMETRIC PYRHELIOMETERS

Yu. A. Sklyarov

ABSTRACT

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The following are computed for a single-layer pyrheliometer with a sensor consisting of a wire spiral: the effect of heat transfer through the wires which serve as supports and current conductors, as well as the difference in the position of heat sources during the illumination and during the heating produced by the current. The nonconductive parts of the spiral consisting of cement and a black coating are taken into account.

The investigations of the P. V. V'yushkov pyrheliometer in 1951-1953 (refs. 1 and 4) have shown the suitability of this method for the absolute measurement of direct solar radiation. To clarify the question concerning the pyrheliometer scale, three V'yushkov pyrheliometers designed by the author were built at the Scientific Research Institute of Mechanics and Physics at the Saratov University. We shall evaluate the possible systematic errors inherent in this device.

1. The radiation sensor of the bolometric pyrheliometer is a two-dimensional, single-layer spiral made of enameled copper wire with a diameter of approximately 0.05 mm, bifilar wound and connected to one of the arms of a measuring bridge. The remaining arms of the bridge are made of heavy manganin wire, and the arm which is symmetric to the sensor with respect to the null--galvanometer is replaceable.

When the spiral is illuminated, a certain amount of current flows through it to balance the bridge. Wnen the spiral is darkened, equilibrium is achieved by increasing the current. By knowing both values of the current, the resistance, the area and the absorption power of tne sensor, it is possible to determine the intensity of direct solar radiation in absolute units.

The radiation sensor of the pyrheliometer is suspended from an adjustable metal ring by tension wires (fig. 1). With other conditions equal, the fluxes of heat through the tension wires to the ring will be different, depending on whether the tube of the device is open or closed. In the first case part of

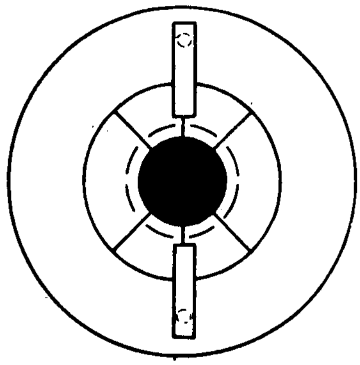

Figure 1.

the tension wires is illuminated by the sun (the broken line in fig. 1 shows the minimum diaphragm). This is the factor responsible for the error in the measured intensity of direct solar radiation introduced by the tension wires.

Let us assume that the temperature of the lower surface of the sensor in both cases (sun--shadow) is the same and equal to t_o. In the future we consider t the excess temperature over the temperature of the air and of the ring. The length of the darkened part of the tension wire is d, while the total length is l. At the center the temperature for all tension wires is considered to be equal.

As we know, the quantity of heat transmitted by the sensor through the tension wire may be expressed in the following manner

$$q = -\lambda \left(\frac{dt}{dx}\right)_{x=0} s.$$

Here λ is the coefficient of heat conductivity, and S is the area of the transverse cross section of the tension wire. We wish to find the temperature distribution in the tension wire when the tube of the pyrheliometer is open and when it is closed.

When the tube of the device is open, the curve for t will consist of two parts: the illuminated and nonilluminated parts of the tension wire which transform into each other.

In the illuminated part of the tension wire (fig. 2) the variation in t will be described by the equation (e.g. refs. 3 and 6).

$$\frac{d^2t}{dx^2} - \alpha^2 t + I\gamma = 0,$$

where $\alpha = \sqrt{\frac{Kp}{\lambda s}}, \gamma = \frac{\beta\delta}{\lambda s}, I$ is the intensity of direct solar radiation, β is the absorption coefficient of the illuminated surface of the tension wire, K is the

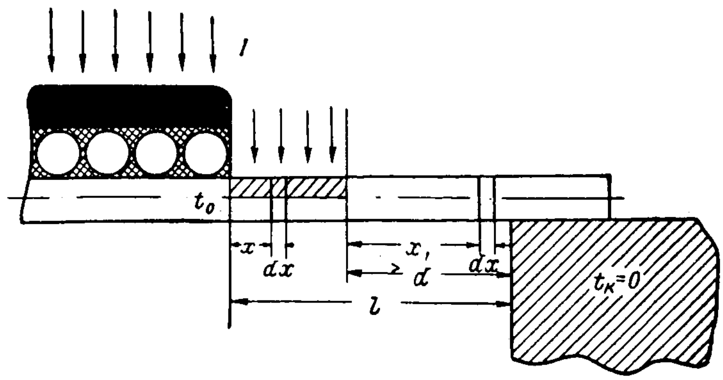

Figure 2.

coefficient of heat transfer, p is the perimeter, S is the area of the cross section, δ is the diameter and λ is the coefficient of internal heat conductivity of the tension wire.

For the nonilluminated part we have equation

$$\frac{d^2t_1}{dx_1^2} - \alpha^2 t_1 = 0.$$

The general solutions of these equations will be as follows:

$$t = Re^{-\alpha x} + Ke \quad + I\frac{\gamma}{\alpha^2} \text{ and } t_1 = Me^{-\alpha x_1} + Ne^{\alpha x_1}.$$

The boundary conditions and the conditions at the junctions t and t_1 will be as follows

$$t = t_0 \text{ for } x = 0, \quad t_1 = 0 \text{ for } x_1 = d;$$
$$t_{x=l-d} = t_{1_{x_1=0}}, \quad \left(\frac{dt}{dx}\right)_{x=l-d} = \left(\frac{dt_1}{dx_1}\right)_{x_1=0}$$

The latter is true because the tension wire is not infinitely thin and consists of the same material.

These conditions give us equations from which we can determine the constants

$$t_0 = R + K + I\frac{\gamma}{\alpha^2},$$

$$Re^{-\alpha(l-d)} + Ke^{\alpha(l-d)} + I\frac{\gamma}{\alpha^2} = M + N,$$
$$-Re^{-\alpha(l-d)} + Ke^{\alpha(l-d)} = -M + N,$$
$$Me^{-\alpha d} + Ne^{\alpha d} = 0.$$

By determining R and K from these equations we obtain an expression for t

$$t = \frac{t_0 + I\frac{\gamma}{\alpha^2}\left(e^{-\alpha l}\operatorname{ch}\alpha d - 1\right)}{1 - e^{-2\alpha l}} e^{-\alpha x} + \frac{t_0 + I\frac{\gamma}{\alpha^2}\left(e^{\alpha l}\operatorname{ch}\alpha d - 1\right)}{1 - e^{2\alpha l}} e^{\alpha x} + I\frac{\gamma}{\alpha^2}.$$

If we take $\left(\frac{dt}{dx}\right)_{x=0}$, and perform a series of transformations, we obtain the following final equation for the heat flux through the initial section of the tension wire when it is illuminated

$$q_{\odot} = \lambda\alpha s t_0 \operatorname{cth}\alpha l - \frac{I\gamma\lambda s}{\alpha}\left[\frac{\operatorname{ch}\alpha l - \operatorname{ch}\alpha d}{\operatorname{sh}\alpha l}\right]. \qquad \text{(a)}$$

In the case of the closed tube, the equations for the distribution of t in the tension wire will be

$$\frac{d^2 t}{dx^2} - \alpha^2 t = 0.$$

Its solution $t = Ae^{-\alpha x} + Be^{\alpha x}$ must satisfy the following boundary conditions

$t = t_0$ for $x = 0$ and $t = 0$ for $x = 1$.

By carrying out all the necessary operations we obtain

$$q_{D} = \lambda\alpha s t_0 \operatorname{cth}\alpha l. \qquad \text{(b)}$$

We can see that when we have solar illumination, the flux of heat through the tension wire (a) is smaller than through (b) by the amount of the second term in (a), which expresses the variation in q as a function of the length of the illuminated part of the tension wire.

To take into account the error in the intensity of the direct solar radiation which results from this, we write the equation for the thermal balance of the sensor in both cases

$$I\rho S_0 + E_{\odot} = hS_0 t_0 + 4\lambda\alpha s t_0 \operatorname{cth}\alpha l - \frac{4I\gamma\lambda s}{\alpha}\left[\frac{\operatorname{ch}\alpha l - \operatorname{ch}\alpha d}{\operatorname{sh}\alpha l}\right],$$

$$E_{D} = hS_0 t_0 + 4\lambda\alpha s t_0 \operatorname{cth}\alpha l.$$

Here ρ is the absorption power of the radiation sensor, S_0 is its area, $E_{\odot}$ and E_D is the energy liberated by the current in the illuminated and darkened sensor and h is the combined coefficient of heat release for the surface of the sensor. In our case we have 4 tension wires, therefore we introduce the coefficient 4.

From these equations we obtain

$$I\left(1 + 4\frac{\gamma\lambda s}{\rho\alpha S_0}\left[\frac{\operatorname{ch}\alpha l - \operatorname{ch}\alpha d}{\operatorname{sh}\alpha l}\right]\right) = \frac{E_D - E_{\odot}}{\rho S_0} = W.$$

The right part W expresses exactly the intensity of radiation determined from the principle on which the device operates. Thus, due to the effect of the tension wires, it is necessary to correct W by a quantity shown in brackets.

$$I = \frac{W}{1 + 4\frac{\gamma\lambda s}{\rho\alpha S_0}\left[\frac{\operatorname{ch}\alpha l - \operatorname{ch}\alpha d}{\operatorname{sh}\alpha l}\right]}.$$

We can see from the equation that if d = 1, i.e., if the tension wire in both cases is darkened, then I = W. The maximum correction is obtained when d = 0, i.e., when the entire tension system is illuminated.

The tension wires and the diaphragm which we used in 1953 had the following specifications: l = 0.6 cm; d = 0.4 cm; δ = 0.005 cm; $\lambda \simeq 1$ (copper); k = 0.0004 cal/cm^2 sec (determined by us experimentally from the thermal balance of the sensor which agrees closely with data published in the literature); β = 0.8; ρ = 0.985, and the area of the radiation sensor S_0 = 0.6 cm^2.

With these data we obtained $I = \frac{W}{1 + 0.0045} = W \cdot 0.9955$, i.e., to eliminate the effect of tension wires it is necessary to reduce the intensity of radiation obtained by the pyrheliometer by approximately 0.5 percent.

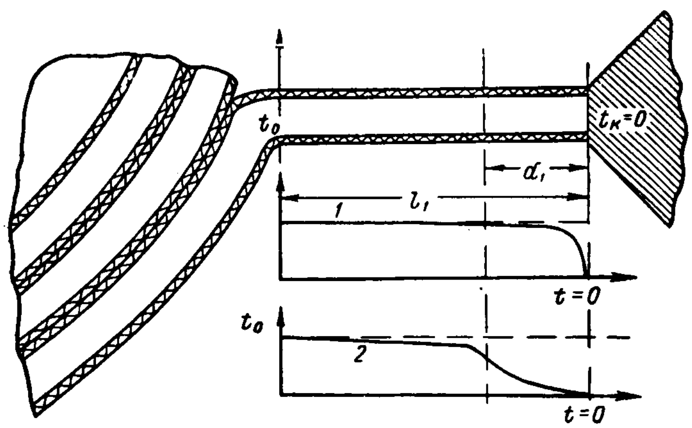

Figure 3.

2. The effect of the ends of the sensor which conduct the current (fig. 3) will be different. In our case they had a length of 3 mm, consequently 2 mm are exposed during solar illumination, while 1 mm is not exposed. These lead conductors are part of the radiation sensor. The part of their surface subjected to radiation was included in the effective area of the sensor.

The thermal stationary state of the sensor when the tube is closed occurs when the current in it has a certain value i_D. Under this condition the lead conductor is heated over the entire length starting at the junction with the contact plate. The temperature distribution in it is represented by curve 1 (fig. 3). During exposure to the sun and the establishment of the same temperature of the sensor, only part of the lead conductor $(l_1 - d_1)$ is illuminated while in the remaining part the current which flows is equal to $i_\odot$.

If we did not have $i_\odot$, then the variation in the temperature of the lead conductor would be given by curve 2, i.e., we would observe in it, in the ideal case, an edge defect which would lower the reading.

Without carrying out calculations we note the following: (1) If, in the Angström pyrheliometer the edge effect refers to the entire radiation sensor, then in our case it occurs only for the lead conductors; (2) In this case the magnitude of the edge effect is lowered due to the current in the conductor which makes the variation in the temperature curve approach case 1 (fig. 3); (3) If the edge effect for the conductor in our case is several percent, then, in determining the radiation, this error will be introduced with a weight factor close to the ratio of the illuminated area of the conductor to the entire area of the radiation sensor. This ratio is less than 10^{-2}. Consequently, the bolometric pyrheliometer is practically free of the edge effect.

3. The measured radiation heats the radiation sensor from the surface. The thermal flux formed in the darkened surface heats the spiral, and passes through the layer of soot which cements the film and the insulation of the wire. The temperature of the sensing surface in this case will be greater than the temperature of the spiral. However, when the spiral is heated by the current to an equal temperature, which is controlled by the bridge, based on the equivalence of the resistance of the spiral in both cases, the temperature of the sensing area will be less than the temperature of the spiral. This inequality in the conditions of heat transfer of the sensing surface in both cases leads to a lowering of the measured values of radiation.

An error of this type was determined to take into account the effect of the shell of the thermometers during the nonstationary thermal state (ref. 5). For the stationary state this effect was investigated as it applies to the Angström pyrheliometer (ref. 6).

In both cases the necessary correction was introduced by multiplying the results of the measurements by an expression of the form $1 + \alpha \frac{d}{\lambda}$. Here α is the coefficient of heat released by the sensing surface, d is thickness and λ is the coefficient of heat transfer of the layers between the sensing surface and the body whose temperature is being measured.

In the bolometric pyrheliometer the radiation sensor is not continuous. Double layers of enamel insulation and cement are placed between the turns of the wire, and the thermal conductivity of these is equal to 10^{-3}, less than the thermal conductivity of copper. The thickness of the enamel insulation of the wires with a diameter up to 0.09 mm is equal to 0.008 mm. Therefore, even when the spiral is tightly wound, the intervals of low thermal conductivity between the turns will comprise 15-30 percent of the total area of the sensor, depending on the wire used to wind the spiral. This may introduce an additional error when measuring radiation with this device.

The effect of the layers between the turns may be taken into account, if we evaluate the magnitude of the thermal flux from the heated conductors through these layers.

Let us consider two adjoining turns of the spiral with insulation between them. We shall assume that these turns at the selected region are parallel and that there is no heat transfer along their length. For simplification we replaced the round wire with a square wire, whose diagonal is equal to the diameter of the spiral wire. Let us assume that the interval between these sides of the square wire is completely filled with insulation which, of course, will only increase the investigated effect. Let us assume also that the coefficient of heat released is the same for the upper and lower surfaces.

With these assumptions, the distribution of the lines of heat flux in the insulation between the conductors is shown in figure 4. The z axis is directed upwards, perpendicular to the plane of the drawing.

It is clear that a thermal flux released by the surface of the wire of height a will flow through the insulation over the area of unit length in the direction of the z axis and of width L.

During the stationary process, the temperature field in the insulation must satisfy the following conditions

(1) The function $\vartheta = \vartheta(x,y)$ must be a solution of the Laplace equation

$$\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} = 0,$$

because there are no internal sources of heat in the entire volume of the insulation. For ϑ we take the dimensionless expression for the temperature rise $\vartheta = \frac{t - t_0}{t_1 - t_0}$. Here t is the temperature at any point, t_0 is the temperature of the cooling medium and t_1 is the temperature of the wire.

(2) $-\lambda \frac{\partial \vartheta}{\partial x} = \alpha \vartheta$ when $x = \pm a$ (along L);

(3) For $y = 0$, $\vartheta = 1$ when $-a < x < a$;

(4) $\frac{\partial \vartheta}{\partial y} = 0$ when $y = L$.

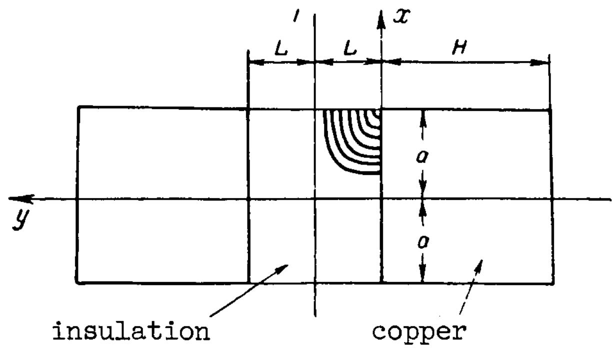

Figure 4.

A similar problem is solved in reference 6.

The general solution of the Laplace equation, which satisfies all of the boundary conditions, has the form

$$\vartheta = \sum_{k=1}^{\infty} A_k \frac{\mathrm{ch}\,[n_k (L-y)]}{\mathrm{ch}\,(n_k L)} \cos (n_k x). \tag{1}$$

Here n_k is obtained from the roots of the transcendental equation

$$\delta_k = \frac{\alpha}{\lambda} a \,\mathrm{ctg}\, \delta_k, \tag{2}$$

in which

$$\delta_k = n_k a;$$

α is the coefficient of heat released from the surface and λ is the heat transfer coefficient of the insulation; a and L are clear, as shown in figure 4.

To compute the coefficients A_k we use the equation

$$A_k = \frac{2 \sin \delta_k}{\delta_k + \sin \delta_k \cos \delta_k}. \tag{3}$$

Let us carry out the calculation for an actual wire used for the spirals, which has a thickness of 0.08 mm, or for a square wire with sides 0.06 mm and, consequently with a = 0.03 mm. In this case the distance between the adjoining square wires is 0.04 mm, while L = 0.02 mm. We assume that α= 12 watt/meter^2 degree. λ = 18 watt/meter degree; in these calculations we use data which are expressed in the engineering system of units.

Then $\frac{\alpha}{\lambda}$ a = 0.002. For such small values of $\frac{\alpha}{\lambda}$ a, reference (2) does not give the values for the roots of equation (2).

By using Newton's method of successive approximations we obtain the following values for the roots δ_1 = 0.0447; δ_2 = 3.1422; δ_3 = 6.2835, and δ_4 = 9.4250.

With these roots for equation (2), we use equation (3) to compute the values of the coefficients A_k: $A_1 = 1.0001$; $A_2 = -0.0004$; $A_3 = 0.0001$, and $A_4 = 0.0000$.

For control purposes we use the condition $\Sigma A_k = 1$, which in our case gives us $\Sigma A_k = 0.9998$, i.e., the unknown solution (1) with an accuracy up to 0.02 percent represents the true distribution of temperature in the insulation layer.

The average density of the thermal flux which passes through the region of insulation of width L is computed by means of the equation

$$w_L = \frac{t_1 - t_0}{L} \lambda \sum_{k=1}^{\infty} A_k \operatorname{th}(n_k L) \sin(n_k a), \tag{4}$$

where $(t_1 - t_0)$ is the increment in the temperature of the copper wire.

Assuming that $(t_1 - t_0)$ is equal to 20° C, we obtain $W_L = 239.80$ watt/meters^2.

A thermal flux will be released directly from the surface of the wire (along H in fig. 4) equal in value to $W_H = \alpha(t_1 - t_0)$. In our case this is equal to 240.00 watt/meters^2.

Thus, a flux branches through the insulation between the wires and differs from the flux from the surface of the wire by 0.08 percent.

Calculations made for identical conditions of heat transfer give the following results for different values for L.

When L is equal to 0.04, 0.05, and 0.10 mm, the density of the thermal flux through the insulation differs from the density of the thermal flux from the surface of the conductor by 0.2, 0.3, and 0.8 percent, respectively.

When the spiral is tightly wound with round wire, the distance between adjoining conductors will be equal to twice the thickness of the insulation, i.e., in our case 0.02 mm. In this case the difference between the considered fluxes will be less than 0.08 percent.

The existing individual regions of low density on the winding between the turns of the spiral filled with cement do not exceed 0.03 mm in thickness. Consequently, their effect on the thermal flux which passes through these layers will be of the order of 0.10-0.15 percent.

The calculations were made under the assumption that heat emission takes place directly from the surface of the conductors and from the layers of insulation between them. It is clear that the presence of insulating layers and of soot over the surfaces $x = \pm a$, which actually takes place, will contribute to the compensation of both of these fluxes.

The curvature of the conductors and of the insulation layers between them leads to a variation in the density of the thermal flux which passes through the insulation. The maximum value of such variation is obtained, if we assume that the thermal flux has passed along the radial direction of the spiral through the insulation to the neutral surface and is only then released by the heat emitting surface. In this case

$$\frac{w_L}{w_a} = \frac{r}{r + L}.$$

Here W_L is the density of the thermal flux which passes through the insulation layer of thickness L, W_a is the density of the thermal flux on the surface of the conductor a, and r is the radius of curvature of the surface of conductor a. Because L is small compared with r (L = 0.02 mm, while r is small only in the first central turns, the radius of the spiral, however, is equal to 4.5 mm), the ratio $\frac{r}{r + L}$ is practically equal to unity for almost all the turns of the spiral.

Consequently, the proposition of the parallel nature of adjoining turns of the spiral, which was assumed in the calculation, corresponds to true conditions for thin layers of insulation between the turns.

Some lack of symmetry in the conditions between the turns of the spiral may be produced by the presence of a temperature gradient from the center of the spiral to the edge, due to heat emission along the perimeter of the edge turn. However, because there are insulation layers between the turns and because the current density in the spiral wire is the same, this may be encountered in practice only under conditions existing in the edge turn.

Thus, we can make a final conclusion, namely, that the thin spiral tightly wound behaves like a homogeneous plate in the process of heat transfer.

Because the spiral, within the limits of wire thickness without insulation, may be considered as a homogeneous plate, it is easy to evaluate the magnitude of the error produced by the difference of heating by the current and by radiation.

Let us assume that α_1, and α_2 are the heat emission coefficients of the upper (sensing) and lower surfaces of the spiral, δ_1, λ_1 and δ_2, λ_2 are the thicknesses and the heat transfer coefficients of the insulating layers, respectively, where λ_1 is the combined coefficient of heat conductivity for the layers of enamel insulation, the cementing film and the soot. The heat conductivity of copper is greater by three orders of magnitudes than that of the above layers; therefore, the temperature drop in the copper wire may be neglected and it may be assumed to be the same in both cases of heating.

The variation of the temperature in the radiation sensor during illumination will be represented by the broken line $t_1 t_0 t_2$ in figure 5, where t_1 is the temperature of the sensing surface. In this case a thermal flux $W_\odot$, produced by the compensating current, is liberated in the spiral.

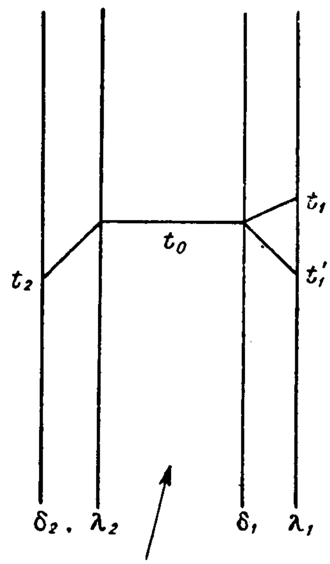

Figure 5.

Let us assume the intensity of the incident radiation to be I (in the bolometric pyrheliometer $W_\odot < I$). Then some thermal flux will pass through the sensor from the sensing surface (in the direction of t_1 to t_2)

$$I - \alpha_1 t_1 = \alpha_2 t_2 - w.$$

Here t represents the temperature excesses of the surfaces compared with the temperature of the surrounding medium.

Expressing t_1 and t_2 in terms of t_0, and in terms of the other parameters, we obtain

$$I = t_0 \frac{\alpha_1 + \alpha_2 + \alpha_1 \alpha_2 R}{1 + \alpha_2 \frac{\delta_2}{\lambda_2}} - w_\odot \left(1 + \alpha_1 \frac{\delta_1}{\lambda_1}\right), \tag{5}$$

where $R = \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}$.

When the tube is closed, compensation is achieved by means of the current, and in this case energy W_D is released. The variation of the temperature in the sensor in this case is represented by the line $t_1't_0\ t_2$, because, when we compensate for the temperature of the copper wire, the same line $t_1't_0t_2$ will coincide with $t_1t_0t_2$ along the region t_0t_2.

In a similar manner, for this case we obtain

$$w_{\text{т}} = t_0 \left[\frac{\alpha_1 + \alpha_2 + \alpha_1\alpha_2 R}{\left(1 + \alpha_1 \frac{\delta_1}{\lambda_1}\right)\left(1 + \alpha_2 \frac{\delta_2}{\lambda_2}\right)} \right]. \tag{6}$$

Eliminating t_0 from expressions (5) and (6), we obtain

$$I = (w_{\text{т}} - w_{\odot})\left(1 + \alpha_1 \frac{\delta_1}{\lambda_1}\right). \tag{7}$$

Here $(W_D - W_{\odot})$ is the energy difference of the compensating currents for a closed and open tube of the device, i.e., the magnitude of the radiation obtained from measurements made by means of the bolometric pyrheliometer.

The value of radiation free from the investigated error is obtained by multiplying the results of the measurements by a term of the form $1+\alpha_1\frac{\delta_1}{\lambda_1}$ It coincides with similar correction terms used in references 5 and 6, although it is obtained under several different assumptions. Apparently the expression of the form $1+\alpha_1\frac{\delta_1}{\lambda_1}$ is quite general in establishing corrections for errors of this type.

In order to evaluate the magnitude of the possible errors of this effect, we assume that $\alpha = 12$ watt/meter^2 degree, that the combined thickness of the insulation layers and of the soot is $\delta_1 = 1 \cdot 10^{-4}$ meter, and that the average thermal conductivity of the layers is $\lambda = 0.15$ watt/meter degree, which is very close to actual conditions. Then

$$I = (W_D - W_{\odot}) \cdot 1.008,$$

i.e., the reading of the device must be increased by 0.8 percent.

It is necessary to point out that for α_1 we must take the combined value of the coefficient of heat emission, due both to conduction and to radiation. The value of α_1 depends very strongly on the cooling conditions and especially on those due to the wind. Consequently, in order to make an accurate estimation of the error caused by the difference in the methods of heating the spiral by radiation and by the current, it is necessary to take into account, accurately, the parameters which enter into equation (7).

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